

# Precision Measurements of Electroweak Parameters with Z Bosons at the Tevatron

Arie Bodek for the CDF and D0 collaborations

*Department of Physics and Astronomy,*

*University of Rochester, Rochester, NY. 14627, USA*

Proceedings of the Third Annual Large Hadron Collider Physics Conference

LHCP15, Aug. 31-Sept 5, 2015 Saint Petersburg, Russia

## ABSTRACT

We report on the extraction of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  and an indirect measurement of the mass of the W boson from the forward-backward asymmetry of dilepton events in the Z boson mass region at the Tevatron. The data samples of  $e^+e^-$  and  $\mu^+\mu^-$  events collected by the CDF detector correspond to the full  $9.4 \text{ fb}^{-1}$  run II sample and yield an effective electroweak mixing angle  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23222 \pm 0.00046$ . The corresponding result reported by the D0 collaboration with the full  $9.4 \text{ fb}^{-1}$   $e^+e^-$  sample is  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23146 \pm 0.00047$ . The CDF collaboration also extracts the on-shell electroweak mixing angle  $\sin^2 \theta_W = 0.22401 \pm 0.00044$  which corresponds to an indirect measurement of the W boson mass  $M_W(\text{indirect}) = 80.327 \pm 0.023 \text{ GeV}$ . The quoted uncertainties include both statistical and systematic contributions.

## 1 Introduction

The effective  $\sin^2 \theta_W$  coupling at the lepton vertex, denoted as  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$ , has been accurately measured at the LEP-1 and SLD  $e^+e^-$  colliders. The combined average of six individual LEP-1 and SLD measurements[1] yields  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23153 \pm 0.00016$ . However, there is tension between the two most precise individual measurements: the combined LEP-1 and SLD  $b$ -quark forward-backward asymmetry ( $A_{\text{FB}}^{0,b}$ ) yields  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23221 \pm 0.00029$ , and the SLD polarized left-right asymmetry ( $\mathcal{A}_\ell$ ) yields  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23098 \pm 0.00026$ . These two measurements differ by 3.2 standard deviations. In order to help resolve this difference new measurements of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  should have uncertainties similar to SLD or LEP ( $\approx \pm 0.0003$ ).

In addition, now that the Higgs boson mass ( $M_H$ ) is known, the Standard Model (SM) is over constrained. Any inconsistency between precise measurements of SM parameters could be indicative of new physics. Fig.1 (a) (from ref.[2]) shows the current world average[3] of direct measurements of the mass of the W boson ( $M_W = 80.385 \pm 0.015 \text{ GeV}$ ) versus the 2014 average[4] of the direct measurements of the mass of the top quark ( $M_t = 173.34 \pm 0.76 \text{ GeV}$ ).

The average of the Tevatron measurements of  $M_t$  in 2014 is  $M_t = 174.34 \pm 0.37(\text{stat}) \pm 0.52(\text{syst}) \text{ GeV}$  (or  $174.34 \pm 0.64$ ). If we also include the 2014 measurements of ATLAS and CMS the combined 2014 world average [4] (CDF, D0, CMS, ATLAS) is  $M_t = 173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst}) \text{ GeV}$  (or  $173.34 \pm 0.76 \text{ GeV}$ ) as shown in Fig.1

(a). Also shown in green is the expectation from the SM with  $M_H = 125.6 \pm 0.7$  GeV. The average of all direct measurements of  $M_W$  is about 1.5 standard deviation higher than the prediction of the standard model. Predictions of supersymmetric models for  $M_W$  are also higher [5] than the predictions of the standard model.

The most recent measurement of  $M_t$  at the LHC are somewhat lower than at the Tevatron. The ATLAS[6] measurement published in 2015 is  $M_t = 172.99 \pm 0.91$  GeV. The CMS[7] 2015 measurement  $M_t = 172.44 \pm 0.13(\text{stat}) \pm 0.47(\text{syst})$  GeV (or  $172.44 \pm 0.48$  GeV) is the most precise measurement to date and supersedes all previous CMS results. There is about a two standard deviation tension between the 2015 CMS measurement of  $M_t$  and the earlier Tevatron measurements. However, both are consistent with the world average. The lower value of  $M_t$  as measured by CMS

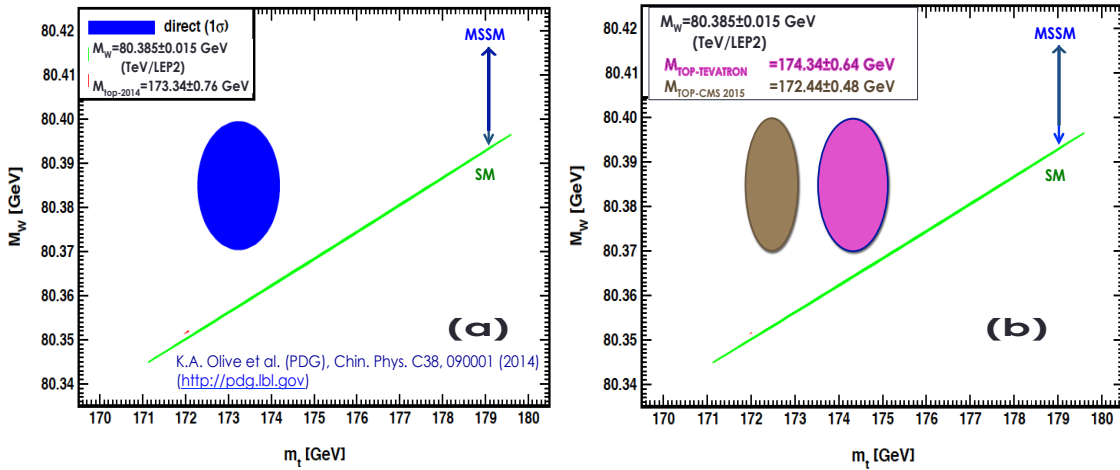


Figure 1: (a) World average of all direct measurements of  $M_W$  (CDF, D0, LEP2) versus the average of all  $M_t$  measurements (CDF, D0, CMS, ATLAS) in 2014. The green line is the expectation from the SM (with  $M_H = 125.6 \pm 0.7$  GeV). Supersymmetry models predict values which are above the SM line. (b) Same as (a) but with the CMS measurement of  $M_t$  in 2015 as compared to the Tevatron measurement of  $M_t$ .

would imply a somewhat larger deviation of  $M_W$  from the prediction of the SM as shown in Fig. 1 (b). The parameter that needs to be measured more precisely is  $M_W$ . The current experimental uncertainties in the direct measurements of the W boson mass ( $M_W^{\text{direct}}$ ) by D0 and CDF at the Tevatron are about  $\pm 20$  MeV per experiment. Equivalently one can also measure the on-shell[8] weak mixing angle,  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ . An error of  $\pm 0.0004$  in the on-shell  $\sin^2 \theta_W$  is equivalent to an indirect measurement of the W boson mass ( $M_W^{\text{indirect}}$ ) to a precision of  $\pm 20$  MeV.

The angular distribution for the production of deletions in hadron colliders is proportional to

$$1 + \cos^2 \theta + \frac{A_0}{2}(1 - 3 \cos^2 \theta) + A_4 \cos \theta,$$

where  $\theta$  is the polar angle in the Collins-Soper frame[9]. The coefficient  $A_0(P_T)$  is small and vanished for dilepton transverse momentum  $P_T = 0$ . The integrated

forward-backward asymmetry  $A_{\text{fb}}(M)$  is equal to  $3A_4(M)/8$ ,

Precise extractions of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  and  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$  using the forward-backward asymmetry ( $A_{\text{fb}}$ ) of dilepton events produced in  $p\bar{p}$  and  $pp$  collisions are now possible for the first time because of four new innovations:

- A new technique [10] for calibrating the muon and electron energy scales as a function of detector  $\eta$  and  $\phi$  (and sign), thus greatly reducing systematic uncertainties from the energy scale. These technique is used at CDF and CMS. A similar technique is used by D0 for electrons.
- A new event weighting technique[11]. With this technique all experimental uncertainties in acceptance and efficiencies cancel (by measuring the  $\cos \theta$  coefficient  $A_4$  and using the relation  $A_{\text{fb}} = 3A_4/8$ ). Similarly, additional weights can be included for antiquark dilution, which makes the analysis independent of the acceptance in dilepton rapidity. These technique is used by CDF and is currently being implemented at CMS.
- The implementation[12] in 2012 of Z fitter Effective Born Approximation (EBA) electroweak radiative corrections into the theory modified predictions of POWHEG and RESBOS which allows for a measurement of both  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  and  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ . These EBA electroweak radiative corrections were implemented in CDF analyses[12, 13, 14] since 2013. Recently, an official version of POWHEG with electroweak radiative corrections has been released. Similarly, electroweak radiative corrections have been implemented in other theory predictions. Comparisons of different implementation of EW radiative corrections are now possible..
- A new technique [15] that reduces Parton Distribution Function (PDF) uncertainties by incorporating additional constraints from the mass and rapidity dependence of Drell-Yan  $A_{\text{fb}}$ . The use of Drell-Yan  $A_{\text{fb}}(M, y)$   $\chi^2$  weighting was first proposed in ref. [15]) for additional constraints on PDFs. The  $\chi^2$  weighting technique reduces the PDF uncertainty in the measurements of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$ ,  $\sin^2 \theta_W$ , and in the indirect and direct measurements of  $M_W$ . This technique has been used in CDF[14] and is currently being implemented in CMS.

## 1.1 Momentum-energy scale corrections

This new technique[10] is used in CDF (for both muons and electrons) and also in CMS. In CMS it is used to get a precise measurement of the Higgs boson mass in the four lepton channel. A similar technique is used by D0 for electrons. The technique used in CDF and CMS relies on the fact that the  $Z$  boson mass is well known as follows:

- Any correlation between the scales of the two leptons is removed by getting an initial calibration using  $Z$  events. It is done by requiring that the mean  $\langle 1/P_T \rangle$  of each lepton in bins of detector  $\eta$ ,  $\phi$  and charge is equal to the expected value for generated  $Z$  events, smeared by the momentum/energy resolution.

- The Z boson mass is used as a second order correction. The measured Z boson mass as a function of detector  $\eta$ ,  $\phi$  and charge of the lepton is required to be equal to the value for generated Z events (smeared by the momentum/energy resolution). Additionally the measured  $J/\psi$  and  $\Upsilon$  masses as a function of  $\eta$  of the lepton are also used.

The scale corrections are determined for both data events and reconstructed hit level Monte Carlo events. After corrections, the reconstructed Z boson mass as a function  $\eta$ ,  $\phi$  and charge for both the data and hit level MC agrees with the generator level Monte Carlo (smeared by resolution, and with experimental acceptance cuts). All charge bias is removed. For muons, the following calibration constants are extracted for each bin in  $\eta$  and  $\phi$

- A multiplicative calibration correction in the quantity  $1/P_T$  which accounts for possible mis-calibration of the magnetic field.
- A calibration correction which is additive in  $1/P_T$  which accounts for tracker mis-alignments.
- For very low energy muons, the  $J/\psi$  and  $\Upsilon$  masses are used to determine a small additional calibration constant to tune the  $dE/dx$  energy loss in the amount of material in the tracker as a function of detector  $\eta$ .

When the technique is used for electrons, the multiplicative correction accounts for tower mis-calibration and there is no additive correction since the tracker is not used in the reconstruction of the electron energy.

## 1.2 The event weighting technique

The forward-backward  $A_{fb}$  asymmetry of leptons measured with this technique[11] is insensitive to the acceptance and lepton detection efficiency. Therefore, the raw  $A_{fb}$  which is measured using this technique is automatically corrected for efficiency and acceptance. The only corrections that need to be made are corrections for momentum/energy resolution which lead to event migration between different bins in dilepton mass. All experiment dependent systematic uncertainties cancel to first order. This technique is used in the CDF analysis for muons and electrons, and is currently being implemented at CMS.

The event weighting technique utilizes two kinds of weights. Angular weights are used to remove the sensitivity to acceptance and lepton detection efficiency as a function of  $\cos\theta$ . In the CDF (and CMS) analyses, only angular weights are used. For proton-proton collisions at the LHC, one can also include weights which correct for the rapidity dependent dilution and therefore removes the sensitivity to the acceptance in dilepton rapidity.

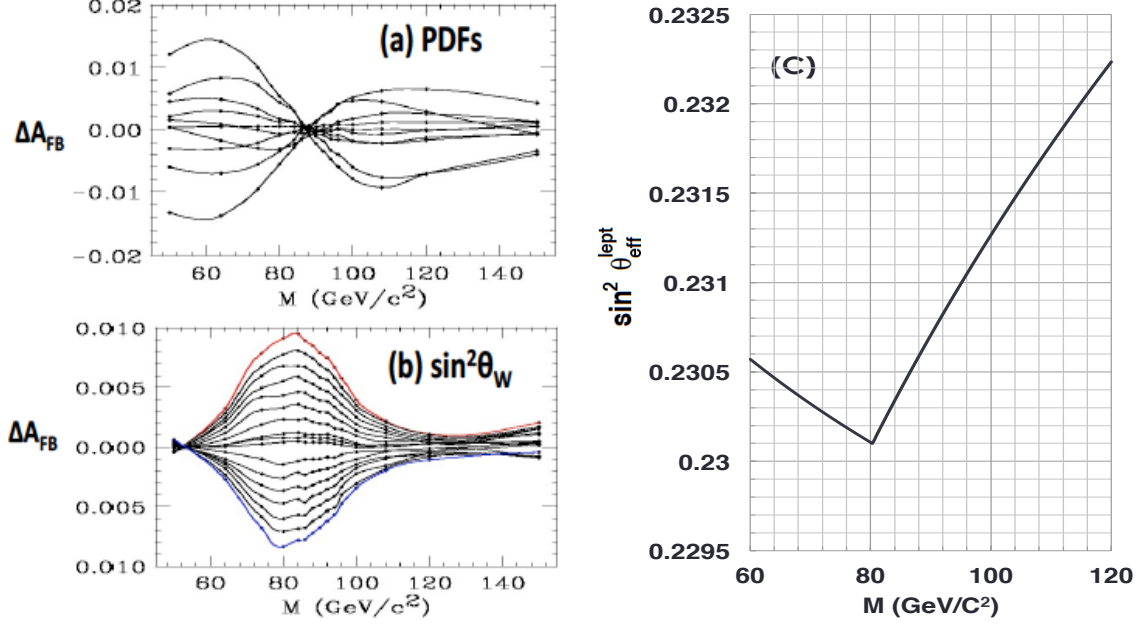


Figure 2: Tevatron: (a) The difference between  $A_{fb}(M)$  for 10 NNPDF3.0 (NNLO) replicas and  $A_{fb}(M)$  calculated for the default NNPDF3.0 (NNLO) (261000). Much of the difference originates from the different dilution factors for each of the NNPDF replicas. Here  $\sin^2 \theta_W$  is fixed at a value of 0.2244. (b) The difference between  $A_{fb}(M)$  for different values of  $\sin^2 \theta_W$  ranging from 0.2220 (shown at the top in red) to 0.2265 (shown on the bottom in blue), and  $A_{fb}(M)$  for  $\sin^2 \theta_W=0.2244$ . Here  $A_{fb}(M)$  is calculated with the default NNPDF3.0 (NNLO). (Figures (a) and (b) are from Ref. [15]). (c) Scale dependence of  $\sin^2 \theta_{eff}^{lept}(M)$ . The minimum of  $\sin^2 \theta_{eff}^{lept}(M)$  is at the mass of the W boson (from Ref. [2]).

### 1.3 Electroweak radiative corrections

#### 1.3.1 zgrad-type EW radiative corrections - used by D0

An approximate method that only corrects for the flavor dependence of  $\sin^2 \theta_{eff}$  has been proposed by Baur and collaborators [18]. The flavor dependence is approximately:  $\sin^2 \theta_{eff}^{u-quark} = \sin^2 \theta_{eff}^{lept} - 0.0001$  and  $\sin^2 \theta_{eff}^{d-quark} = \sin^2 \theta_{eff}^{lept} - 0.0002$ .

We refer to these EW corrections (which have been implemented in RESBOS) as ZGRAD-type corrections. These corrections are used by D0. The D0 collaboration reports[19] that  $\sin^2 \theta_{eff}^{lept}(M_Z)$  extracted using RESBOS (with CTEQ 6.6 -NLO PDFs) including ZGRAD-type radiative corrections is +0.00008 larger than the value of  $\sin^2 \theta_{eff}^{lept}(M_Z)$  extracted using PYTHIA 6.323 [20] with the same PDF set and no EW radiative corrections. The PYTHIA matrix elements are QCD leading order as compared to RESBOS matrix elements which are NLO. However, as reported by D0, the estimated correction due to higher order QCD effects is negligibly small.

The above procedure partially corrects for the flavor dependence of  $\sin^2 \theta_{eff}$ . It does not account for the mass dependence of  $\sin^2 \theta_{eff}$  (shown in Fig. 2(c)) nor does it account for the complex mass dependent form factors. As described below, a more

complete treatment of EW radiative corrections factors is needed in order yield a measurement of the on-shell  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ .

### 1.3.2 Effective Born approximation (EBA) electroweak radiative corrections - used by CDF

These radiative corrections have been implemented in CDF[12] (for modified versions of POWHEG, RESBOS and Tree level calculations). The corrections are derived from the approach adopted at LEP[16]. The Z-scattering-amplitude form factors are calculated by ZFITTER 6.43 [16] which has been used by LEP-1 and SLD measurements for precision tests of the standard model [17].

$A_{fb}(M)$  in the region of the mass of the Z boson is sensitive to the effective weak mixing angle  $\sin^2 \theta_{\text{eff}}(M, \text{flavor})$ , where  $M$  is the dilepton mass. Here,  $\sin^2 \theta_{\text{eff}}$  is related to the on-shell[8] electroweak mixing angle  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$  via complex mass and flavor (weak isospin) dependent electroweak radiative corrections form factors. The massless-fermion approximation is used.

The parameter which is measured at LEP and SLD is  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$ . Previous extraction of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  from Drell-Yan  $A_{fb}$  neglected the dependence of  $\sin^2 \theta_{\text{eff}}$  on flavor and dilepton mass. The input to the theory predictions has been one value of  $\sin^2 \theta_{\text{eff}}$  which on average was assumed to be independent of mass or flavor and has been interpreted as  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$ .

When the full EBA EW radiative corrections are included, the input to the theory prediction templates for  $A_{fb}(M)$  is the on-shell  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ . The templates are compared to the data and the best fit value of  $\sin^2 \theta_W$  is extracted. From the best fit value of  $\sin^2 \theta_W$  and the full complex EBA radiative corrections form factors we can then extract  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  which is the effective leptonic EW mixing angle at the mass of the Z boson. With the EBA radiative corrections used at CDF it is found that  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) \approx 1.037 \sin^2 \theta_W$ .

If the EBA EW radiative corrections are included, the extracted value of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  is higher by +0.00023 than the value extracted with no EW radiative corrections. About +0.00008 originate from accounting for the flavor dependence of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M)$ , +0.00006 originates from accounting for the mass dependence of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M)$ , and +0.00009 originate from accounting for the mass dependent complex EW Fitter form factors.

## 2 Analysis of CDF $\mu^+\mu^-$ and $e^+e^-$ full 9.4 fb $^{-1}$ run II sample

After applying the calibrations and muon and electron scale corrections to the experimental and simulated data,  $A_{fb}(M)$  is measured in bins of  $\mu^+\mu^-$ [13] for and  $e^+e^-$ [14] invariant mass using the event-weighting method. This measurement is denoted as the raw  $A_{fb}(M)$  measurement because the event-weighting method provides a first-order acceptance correction, but does not include resolution unfolding and final-state (FSR) QED radiation. The raw  $A_{fb}$  measurements in bins of the  $\mu^+\mu^-$  and  $e^+e^-$

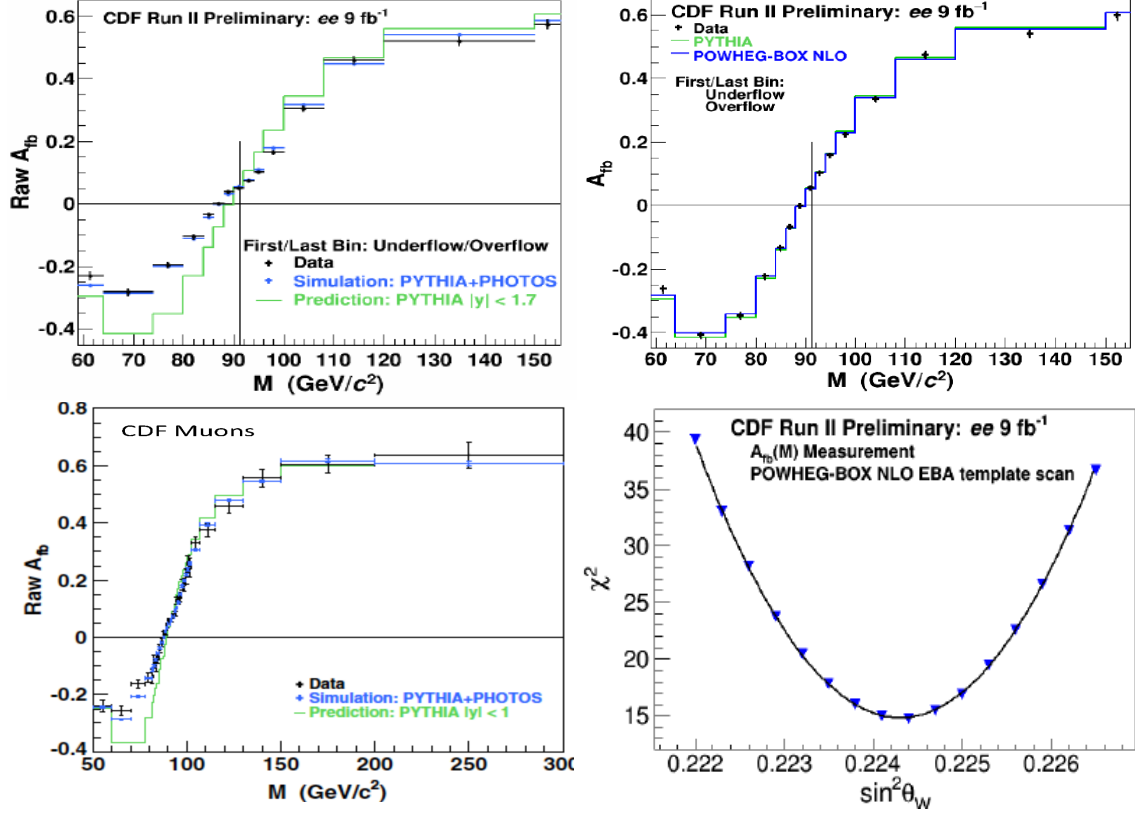


Figure 3: Top-Left: CDF raw  $A_{fb}(M)$  measurement in bins of  $e^+e^-$  invariant mass. Only statistical uncertainties (bin-by-bin unfolding) are shown. The Monte Carlo simulation (PYTHIA) includes the effect of resolution smearing and FSR. The PYTHIA  $|y| < 1.7$  asymmetry curve does not. Top-Right:  $A_{fb}(M)$  for  $e^+e^-$  events unfolded for resolution and QED-FSR. The PYTHIA calculation uses  $\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.232$ . The EBA-based RESBOS and POWHEG calculations uses  $\sin^2 \theta_W = 0.2233$  ( $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.2315$ ). Bottom-Left: Same as Top-Left for the  $\mu^+\mu^-$  sample (here  $|y| < 1$ ). Bottom-Right:  $\chi^2$  vs.  $\sin^2 \theta_W$  for the CDF  $e^+e^-$  sample.

invariant mass are shown on the left part of Fig. 3. Only statistical uncertainties are shown. The Monte Carlo simulation (PYTHIA+PHOTOS) includes the effect of resolution smearing and FSR. To illustrate the effects of resolution smearing and FSR, the PYTHIA  $|y| < 1$  and  $|y| < 1.7$  asymmetry curves do not include the effect of resolution smearing or FSR.

With the event weighting technique, the events near  $\cos \theta = 0$  are assigned zero weight. Therefore, the migration of events between positive and negative  $\cos \theta$  is negligible. Resolution smearing and FSR primarily transfer events between bins in invariant mass. The raw  $A_{fb}$  in bins of  $e^+e^-$  and  $\mu^+\mu^-$  invariant mass is unfolded[13] for resolution smearing and FSR using a transfer matrix which is obtained from the Monte Carlo simulation. The unfolded  $A_{fb}(M)$  for electrons is shown in the top-right panel of Fig. 3.

The electroweak (EWK) mixing parameters  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  and  $\sin^2 \theta_W$  are ex-

tracted from the fully unfolded  $A_{\text{fb}}(M)$  measurements using  $A_{\text{fb}}(M)$  templates calculated with different values of  $\sin^2 \theta_W$ . Three QCD calculations are used: LO (tree), RESBOS NLO, and POWHEG-BOX NLO. The three calculations were modified to include EWK radiative correction[12] using the Effective Born Approximation (EBA).

The  $A_{\text{fb}}(M)$  measurement is directly sensitive to the effective-mixing parameters  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M)$  which are combinations of the form-factors and  $\sin^2 \theta_W$ . Most of the sensitivity to  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  comes from the Drell-Yan  $A_{\text{fb}}(M)$  near the Z pole, where  $A_{\text{fb}}$  is small. In contrast,  $A_{\text{fb}}(M)$  at higher mass values where  $A_{\text{fb}}$  is large, is mostly sensitive to the axial coupling, which is known. While the extracted values of the effective-mixing parameter  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  are independent of the details of the EBA model, the interpretation of the best-fit value of the on-shell  $\sin^2 \theta_W$  and its corresponding form factors depend on the details of the EBA model.

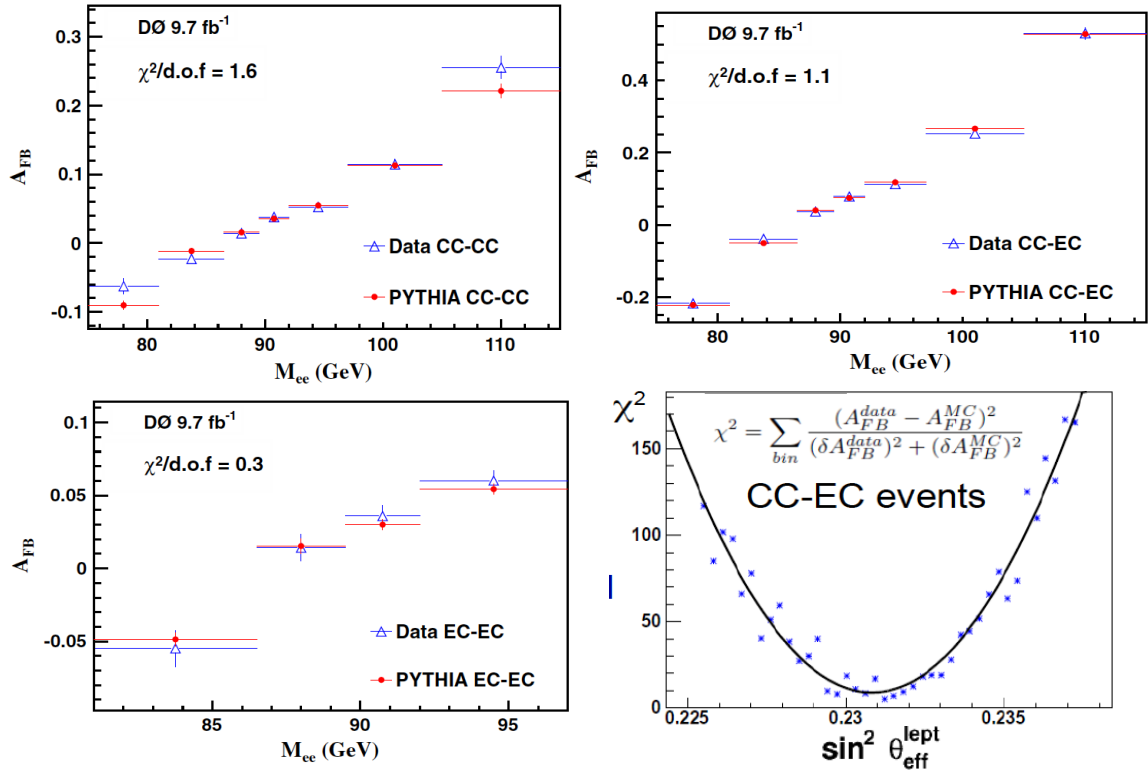


Figure 4: D0 raw  $A_{\text{fb}}(M)$  measurement in bins of  $e^+e^-$  invariant mass for Central-Central calorimeters (CC-CC), Central-Endcap calorimeters (CC-CE), and Endcap-Endcap calorimeters (EC-EC) event topologies. Also shown is the  $\chi^2$  vs.  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  for the D0  $A_{\text{fb}}(M)$  CC-CE topology.

Calculations of the  $A_{\text{fb}}(M)$  templates with different values of the electroweak-mixing parameter are compared with the measurement to determine the value of the parameter that best describes the data. The calculations include both quantum chromodynamic and EBA electroweak radiative corrections. The measurement and templates are compared using the  $\chi^2$  statistic evaluated with the  $A_{\text{fb}}$  measurement error matrix. Each template provides a scan point for the  $\chi^2$  function ( $\sin^2 \theta_W, \chi^2(\sin^2 \theta_W)$ ).



The scan points are fit to a parabolic  $\chi^2$  functional form. For the CDF  $e^+e^-$  analysis, the  $\chi^2$  distribution of the scan over templates from the POWHEG NLO calculation (with NNPDF3.0) is shown in the bottom right panel of Fig. 3. For the  $e^+e^-$  analysis the EBA-based POWHEG box NLO NNPDF3.0 calculations of  $A_{\text{fb}}(M)$  are used to extract the central value of  $\sin^2 \theta_W$ . For the CDF  $\mu^+\mu^-$  analysis the EBA-based RESBOS (CTEQ6.6M) NLO calculations of  $A_{\text{fb}}(M)$  are used to extract the central value of  $\sin^2 \theta_W$ . The other calculations are used to estimate the systematic uncertainty from the electroweak radiative corrections and QCD NLO radiation.

### 3 Analysis of D0 $e^+e^-$ full 9.4 fb $^{-1}$ run II sample

In the published D0 analysis[19],  $A_{\text{fb}}(M)$  measurements in bins of  $e^+e^-$  invariant mass are done for several event topologies as shown in Fig.4. Electrons and positrons are detected in the Central Calorimeter (CC) and in the Endcap Calorimeter (EC). The event topologies correspond to Central-Central (CC-CC), Central-Endcap (CC-CE), and Endcap-Endcap (EC-EC). The effects of acceptance, FSR and resolution smearing are all incorporated into MC templates with different values of  $\sin^2 \theta^{\text{lept}}$ . The RESBOS templates (calculated with NNPDF2.3 NLO PDFs) are compared to the data for the three topologies and the best fit values of  $\sin^2 \theta^{\text{lept}}$  are extracted. The  $\chi^2$  vs.  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  for the D0  $A_{\text{fb}}(M)$  CC-CE topology is shown in the bottom right panel of Fig.4.

#### 3.1 Constraining PDFs through $\chi^2$ weighting

This technique which was first proposed in ref. [15] has been implemented in the most recent CDF analysis[14]. At the Tevatron the technique reduces the PDF uncertainty in  $\sin^2 \theta_W$  by 20%. The reduction of the PDF uncertainty in  $\sin^2 \theta_W$  with this technique at the LHC is much more significant[15]. Fig. 2 (a) from Ref.[15] shows the difference between  $A_{\text{fb}}(M)$  for 10 NNPDF3.0 (NNLO) replicas and  $A_{\text{fb}}(M)$  calculated for the default NNPDF3.0 (NNLO) (261000). Much of the difference originates from the different dilution factors for each of the NNPDF replicas. Here  $\sin^2 \theta_W$  is fixed at a value of 0.2244. Fig.2(b) shows the difference between  $A_{\text{fb}}(M)$  for different values of  $\sin^2 \theta_W$  ranging from 0.2220 (shown at the top in red) to 0.2265 (shown on the bottom in blue), and  $A_{\text{fb}}(M)$  for  $\sin^2 \theta_W=0.2244$ . Here  $A_{\text{fb}}(M)$  is calculated with the default NNPDF3.0 (NNLO).

Fig. 5(a) shows the  $\chi^2$  for the best fit value of  $\sin^2 \theta_W$  at CDF extracted using each of the 100 PDF replicas for the NNPDF3.0 (NNLO) PDF set[21]. As shown in Fig.2(b) different values of  $\sin^2 \theta_W$  raise or lower  $A_{\text{fb}}(M)$  for all values of dilepton mass. In contrast, as shown in Fig.2(a) PDFs which raise the value of  $A_{\text{fb}}(M)$  for dilepton mass above the mass of the Z boson, reduce  $A_{\text{fb}}(M)$  below the mass of the Z bosons. The sensitivity of  $A_{\text{fb}}(M)$  to  $\sin^2 \theta_W$  is very different from the sensitivity to PDFs. Therefore, PDFs with a high value of  $\chi^2$  are less likely to be correct. As shown in ref. [15], this information can be incorporated into the analysis by weighting the PDF replicas by  $e^{-\chi^2/2}$ . This reduces the weights of PDFs with large

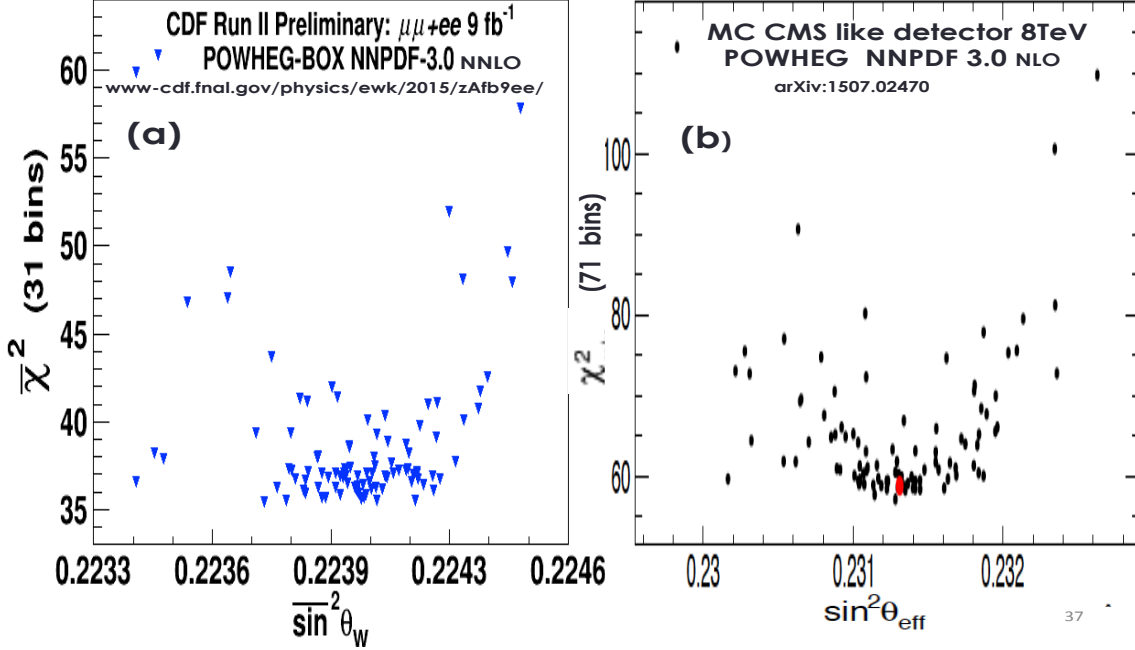


Figure 5: (a) CDF data: Best  $\chi^2$  versus  $\sin^2 \theta_W$  (from ref. [14]). (b) Best  $\chi^2$  versus  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  for MC simulation of a CMS like detector with 15 fb $^{-1}$  at 8 TeV (from ref. [15] (arXiv:1507.02470)).

values of  $\chi^2$ . In addition to the measurements of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  and the on-shell  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ , these  $A_{\text{fb}}(M)$  constrained PDF weights can also be used to reduce the PDF uncertainties in other Tevatron measurements such as the direct measurement of  $M_W$ .

## 4 Results

The Tevatron results with the full 9.4 fb $^{-1}$  sample are:

- D0:  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23147 \pm 0.00043$  (stat)  $\pm 0.00008$  (syst)  $\pm 0.00017$  (NNPDF2.3 NLO PDFs),  
or  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)^{D0} = 0.23147 \pm 0.00047$
- CDF:  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z) = 0.23222 \pm 0.00042$  (stat)  $\pm 0.00008$  (syst)  $\pm 0.00016$  (NNPDF3.0 NNLO PDFs),  
or  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)^{CDF} = 0.23222 \pm 0.00046$
- CDF:  $M_W^{\text{indirect}} = 80.327 \pm 0.021$  (stat)  $\pm 0.010$  (syst) GeV,  
or  $M_W^{\text{indirect}} = 80.327 \pm 0.023$  GeV

The left panel of Fig.6 shows a comparison of  $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z)$  measurement from the Tevatron and other experiments, including the latest LHC results from CMS[22], ATLAS[23] and LHCb[25]. The LEP-1+SLD Z-pole entry is the combination of

their six Z-pole measurements. The right panel of Fig.6 shows a comparison of CDF  $M_W^{indirect}$  measurements to measurements by other experiments. The TeV and LEP-2 value is the world average of the direct measurements[3] of  $M_W$  ( $M_W^{direct} = 80.385 \pm 0.015$  GeV). All the others are indirect W-mass measurements that use the standard model (on-shell scheme). The indirect measurement labeled NuTeV[24] is the Tevatron neutrino neutral current measurement[24]. The indirect measurement labeled LEP1+SLD( $M_t$ ) is from standard model fits to all Z pole measurements[1] in combination with the Tevatron top-quark mass measurement[4].

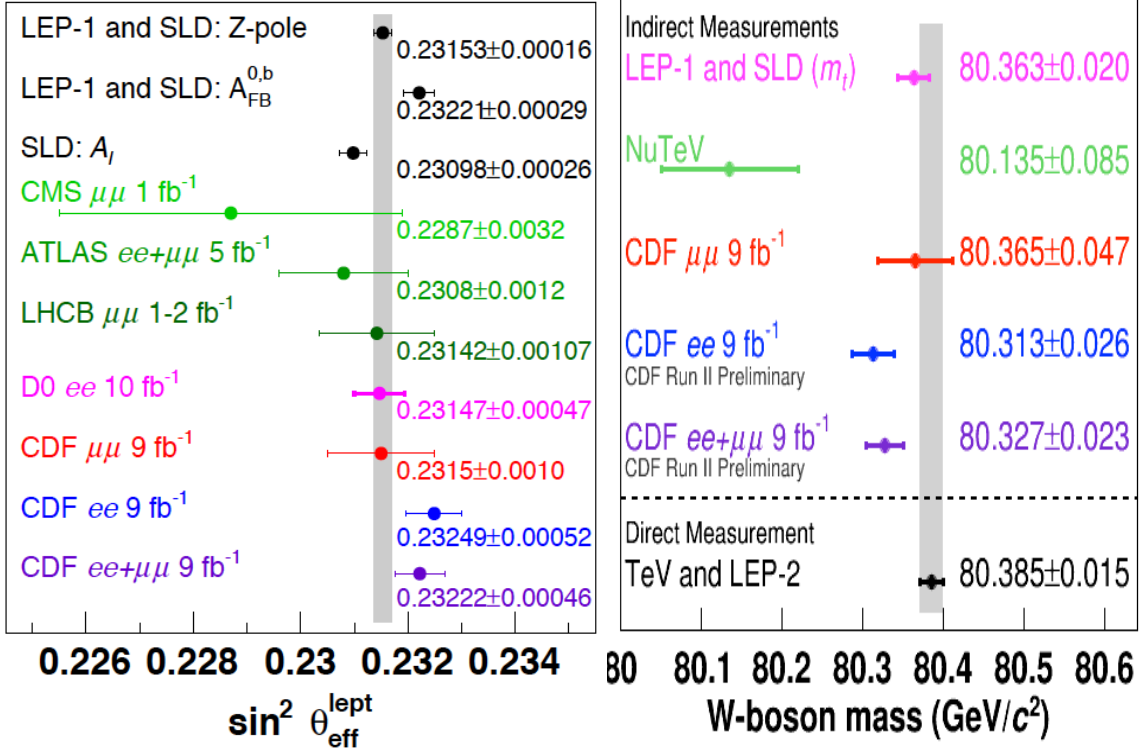


Figure 6: Left panel: Comparison of  $\sin^2 \theta_{eff}^{lept}(M)_Z$  measurements. that includes the latest LHC results from CMS[22], ATLAS[23] and LHCb[25]. The LEP-1+SLD Z-pole entry is the combination of their six Z-pole measurements. Right panel:  $M_W$  measurements. All except for 'TeV and LEP-2' are indirect W-mass measurements that use the standard model (on-shell scheme). NuTeV is the Tevatron neutrino neutral current measurement[24].

## References

- [1] The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups, Phys. Rept. 427, 257 (2006); the ALEPH, DELPHI, L3, OPAL Collaborations, the LEP Electroweak Working Group, Phys. Rept. 532, 119 (2013)

- [2] K.A. Olive et al. (PDG) *Chin. Phys.* **C38**, 090001 (2014). (<http://pdg.lbl.gov>)
- [3] T. Aaltonen et al. (CDF, D0) *Phys. Rev. D* **88**, 052018 (2013), (arXiv:1307.7627).
- [4] ATLAS, CDF, CMS and D0 Collaborations, "*First combination of Tevatron and LHC measurements of the top-quark mass*", arXiv:1403.4427 (ATLAS-CONF-2014-008; CDF Note 11071; CMS PAS TOP-13-014; D0 Note 6416).
- [5] Heinemeyer, W. Hollik, G. Weiglein, L. Zeune, *JHEP* **12**, 084 (2013) (arXiv:1311.1663).
- [6] ATLAS Collaboration, "*Measurement of the top quark mass in the  $t\bar{t} \rightarrow$  lepton + jets and  $t\bar{t} \rightarrow$  dilepton channels using  $\sqrt{s} = 7$  TeV ATLAS data*", *Eur. Phys. J. C* (2015) **75**:330 (arXiv:1503.05427).
- [7] CMS Collaboration, "*Measurement of the top quark mass using proton-proton data at  $\sqrt{s} = 7$  and 8 TeV*" (arXiv:1509.04044).
- [8] A. Sirlin, *Phys. Rev. D* **22**, 971 (1980).
- [9] J. C. Collins and D. E. Soper, *Phys. Rev. D* **16**, 2219 (1977).
- [10] A. Bodek et al., *Eur. Phys. J. C* **72**, 10 (2012), "*Extracting Muon Momentum Scale Corrections for Hadron Collider Experiments*" (arXiv:1208.3710).
- [11] A. Bodek, *Eur. Phys. J. C* **67**, 321 (2010), "*A simple event weighting technique for optimizing the measurement of the forward-backward asymmetry of Drell-Yan dilepton pairs at hadron colliders*" (arXiv:0911.2850).
- [12] Aaltonen et. al., (CDF collaboration), *Phys. Rev. D* **88**, 072002 (2013), "*Indirect measurement of  $\sin^2 \theta_W$  (or  $M_W$ ) using  $e^+e^-$  pairs in the Z-boson region with  $p\bar{p}$  collisions at a center-of-momentum energy of 1.96 TeV*" (arXiv:1307.0770).
- [13] Aaltonen et. al., (CDF collaboration) *Phys. Rev. D* **89**, 072005 (2014) "*Indirect measurement of  $\sin^2 \theta_W$  (or  $M_W$ ) using  $\mu^+\mu^-$  pairs from  $\gamma^*/Z$  bosons produced in  $p\bar{p}$  collisions at a center-of-momentum energy of 1.96 TeV*" (arXiv:1402.2239).
- [14] <http://www-cdf.fnal.gov/physics/ewk/2015/zAfb9ee/>
- [15] A. Bodek, J. Han, A. Khukhunaishvili, W. Sakumoto, "*Using Drell-Yan forward-backward asymmetry to reduce PDF errors in the measurement of electroweak parameters*" (arXiv:1507.02470).
- [16] D. Bardin, M. Bilenky, T. Riemann, M. Sachwitz, and H. Vogt, *Comput. Phys. Commun.* **59**, 303 (1990); D. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, and T. Riemann, *Comput. Phys. Commun.* **133**, 229 (2001); A. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. Grnewald, K. Monig, S. Riemann, and T. Riemann, *Comput. Phys. Commun.* **174**, 728 (2006).

- [17] S. Schael et al. (ALEPH, DELPHI, L3, OPAL, and SLD collaborations; LEP Electroweak Working Group; and SLD Electroweak and Heavy Flavour Groups), Phys. Rep. 427, 257 (2006) *Precision electroweak measurements on the Z resonance*
- [18] U. Baur, O. Brein, W. Hollik, C. Schappacher, and D. Wackeroth, Phys. Rev. D 65, 033007, 2002, *Electroweak Radiative Corrections to Neutral-Current Drell-Yan Processes at Hadron Colliders* (arXiv:0108274).
- [19] V. M. Abazov et al. (D0 collaboration) Phys. Rev. Lett. 115, 041801 (2015), *Measurement of the effective weak mixing angle in  $p\bar{p} \rightarrow Z/\gamma^* e^+e^-$  events* (arXiv:1408.5016).
- [20] T. Sjostrand, P. Eden, C. Feriberg, L. Lonnblad, G. Miu, S. Mrenna, and E. Norrbin, Comp. Phys. Commun. 135, 238 (2001) PYTHIA version v6.323 is used by D0.
- [21] R. D. Ball et al., Nucl. Phys. B867, 244 (2013), *Parton distributions with LHC data*, NNPDFS.
- [22] The CMS collaboration, Phys. Rev D84 112002 (2011), *"Measurement of the weak mixing angle with the Drell-Yan process in proton-proton collisions at the LHC"* (arXiv:1110.2682).
- [23] The ATLAS collaboration, HEP09, 049 (2015), *"Measurement of the forward-backward asymmetry of electron and muon pair-production in pp collisions at  $\sqrt{s}=7$  TeV with the ATLAS detector"* (arXiv:1503.03709).
- [24] G. P. Zeller et. al. (NuTeV), Phys. Rev. Lett. 88, 091802 (2002) and Phys. Rev. Lett, 90, 239902(E) (2003).
- [25] LHCb collaboration, *"Measurement of the forward-backward asymmetry in  $Z \rightarrow \mu\mu$  decays and determination of the effective weak mixing angle"* (arXiv:1509.07645).